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THERMAL BARRIER COATINGS

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ABSTRACT

Thermal barrier coatings offer gas turbines one way to reach fuel flexibility and improved efficiency. Test/analytical results are encouraging for this young technology.

SUMMARY

Thermal barrier coatings (TBCs) offer a way of insulating and protecting the surfaces of cooled turbine components. Many factors must be considered for incorporation in industrial/utility machines. Analytical studies to date indicate significant pay-offs for TBCs if long time performance can be achieved. Much effort remains before these coatings can be considered ready for gas turbine service.

INTRODUCTION

Oxidation, hot corrosion, and erosion are modes of environmental attack that are major life controlling factors for the hot section components of gas turbine engines. Such attack is induced by superalloy surface reactions with constituents of the hot combustion gases. Impurities in the combustion air and/or in the fuels burned react to produce gaseous and liquid constituents which can result in oxidation/hot corrosion while reactions which produce solid particles lead to erosion. Reduction in the useful load bearing area of components by such attack leads to early component failure and increased maintenance costs.

To minimize such attack, there has been a growing trend toward the use of surface protective coatings (ref. 1). Aluminide conversion coatings and M(Ni, Co, Fe)CrAl type coatings and claddings are finding more extensive use in turbines of all types. Research to deposit improved compositions of these types has received continuing support. However, as the combined goals of

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developing gas turbines with wider fuel tolerance and yet with improved efficiency are pursued, alternate coating approaches have also arisen. One of these involves the use of thermal barrier coatings.

Thermal barrier coatings consist of layered or graded oxide, etc./metal coatings having thermal conductivities significantly lower than those of superalloy gas turbine components. Such coatings must be applied on cooled components to be effective. A typical cross-sectional photomicrograph of such a coating is shown in Figure 1. Here an oxide insulating layer is bonded to a superalloy substrate by a reasonably oxidation/hot corrosion resistant bond coating.

Figure 2 further exemplifies this concept. The hot gases impact the insulating oxide surface layer and result in a relatively high surface temperature. However, a sharp temperature drop develops across the oxide and bond coat since the superalloy component is internally air cooled. This coating produces a significant reduction in temperature at the superalloy surface. In contrast, a similar airfoil without the thermal barrier coating develops a higher superalloy surface temperature. The difference between these two superalloy surface temperatures, ΔT, is a major advantage of thermal barrier coatings.

The purpose of this paper is to provide an overview of the factors which must be considered in using thermal barrier coatings as well as to summarize the potential of such coatings and their current status.

FACTORS TO CONSIDER IN USING THERMAL BARRIER COATINGS

First, most thermal barrier coatings are currently being deposited by plasma spraying. Factors important in this process are shown in Figure 3 and include the power settings of the plasma spray torch; the torch-to-substrate distance; the ionization potential and heat capacity of the plasma gas; and the particle size, distribution, thermal properties, and density of the spray powder. These factors control, along with substrate thermal conductivity and temperature, the temperature of the hot particles as they deposit on the surface to be coated, the rates at which they cool, and structure which develops (ref. 2).

Motion of the torch relative to the item being coated influences the structure, uniformity, and reproducibility of the coatings. Figure 4 shows some of the variety of coating mechanical properties that are related to coating structure, thickness and composition. Of course, such properties vary with temperature. A similar situation exists for thermal properties. And, the coating's environmental resistance is also affected by the fuel/air impurities as well as these factors. Since zirconia is an ionic conductor at elevated

temperature, it can rapidly transport oxygen ions to the bond coating interface during exposure. Thus, ionic conductivity also affects environmental resistance.

Other factors for consideration are the phase relationships in the zirconia and zirconia-yttria, -calcia, -magnesia, etc., systems. Figure 5 (ref. 3) shows an equilibrium phase diagram for the zirconia-yttria system. Note that depending on the mole percent of the stabilizing oxide (here yttria) zirconia has a monoclinic crystal structure at lower temperatures but a tetragonal structure at higher temperatures. Once full stabilization is achieved only the cubic phase is present. Figure 6 (refs. 4 and 5) indicates that such phase transformations of partially stabilized zirconia are accompanied by transformational volume changes on both heating and cooling. This figure also shows that after heating to high temperatures, porous oxide materials can undergo shrinkage which is reflected by a permanent negative change in length (ref. 5). Thus, it can be recognized that the oxide layer's behavior is related to the way it was deposited, the specific oxide composition, the temperature it reaches during service, and the environment to which it is exposed.

Similarly, the bond coat performance is sensitive to these same factors. Since this coating must also be environmentally resistant, coating composition is of importance as reflected by the 100 hour-1000^{o} C hot corrosion attack isopleths (ref. 6) shown in Figure 7. Note that the high chromium (Ni-30/40Cr-5/10Al) alloys have low estimated depths of hot corrosion attack. Alloy ductility is also important to minimize oxide/bond coat strains. The alloy environmental resistance versus ductility trade-offs thus require a sound understanding of the service requirements.

Finally, the oxide coating-bond coating-superalloy substrate combination is really a system and adherence across each interface is needed for good performance. Figure 8 presents a schematic illustrating coating adherence considerations. Under the thermal gradients which develop during service, total oxide expansion at the temperatures reached are less (i.e., coefficient of thermal expansion times change in temperature) than that for the bond coating or the superalloy. This gives rise to a large thermal strain at the oxide-bond coating interface if no cracking or plastic deformation occurs. This region, however, is the weakest part of current coatings.

Having considered the coating constituents and the coating-bond coat-superalloy as a system, the next consideration must be for the impact of such coatings on component performance. As previously discussed, one major task of these coatings is to lower the metal temperatures of air-cooled components.

Since creep-rupture lives are dramatically extended by lowering temperatures, the thermal barrier coating has potential for greatly extending mechanical property life. A caution must be raised, however, for turbine blades - where the weight of the coating raises the blade stress. These trade-offs are shown in Figure 9 through simple estimates of the effect of lower temperature and higher stresses on turbine blade life. Here it can be seen that the gain in life due to temperature reduction is significantly greater than the decrease caused by the higher stress due to coating weight. For example, a 60° C decrease in temperature combined with a 10 percent increase in blade stress results in an estimated life improvement of more than a factor of 10.

Such calculated life extensions may, however, never be achieved since gas turbine component life is controlled by many factors as shown in Figure 10. Note that as previously discussed, oxidation/hot corrosion/erosion attack can lead to lives far short of mechanical property controlled limits. The relative positions of these curves are different for every given engine and service condition. However, in each engine the coating life and coated component life must first be raised above the alloy's environmental life limits before long term reliability and cost effectiveness can be achieved.

Since different potential fuels have different impurities and impurity concentrations, thermal barrier coating compositions may well have to be tailored for specific types of fuels.

Thus, based on this discussion a number of potential coating and/or coated component failure mechanisms can be identified. These are presented in Figure 11. Coating deterioration may occur at the oxide surface (a, b, and e), or it may occur within the coating (c, d, and f). Any approach toward improving the environmental resistance of such coatings, of course, will depend on the specific cause and loaction of this degradation.

WHAT IS THE STATUS OF THERMAL BARRIER COATINGS NOW?

Thermal barrier coatings are in the early stages of development as portrayed in Figure 12. In the case of aircraft turbines where gas temperatures can reach 1370° C but very high purity Jet A or JP 5 fuel is burned, some burner rig data and engine tests have been run. These will be reviewed in the following paragraphs. However, only scattered rig data can be found in the literature on "clean" industrial/utility fuel or on doped "clean" fuel tests. For experience on TBC performance in residual fuels or blends, no published data are available.

For aircraft service where high gas temperatures and clean fuels, relatively short exposure cycles, and relatively small airfoils are found, thermal barrier coatings have had limited testing. One such test was in a NASA-Lewis Research Center engine operating at 1 370^{o} gas temperature, low pressure ratios (approx. 3 atm), and short time cycles from full power to flame out (ref. 7). All blades except two in the first stage turbine were coated with NASA's patented two layered zirconia-yttria/MCrAl system (ref. 8). After 500 cycles to 1 060^{o} C surface temperature (900^{o} C metal temperature) no coating distress was observed except some blade tip foreign object damage as shown in Figure 13. Similar temperature drops were observed between coated and uncoated vanes subjected to similar exposures (ref. 9). A JT8D combustor was coated internally at NASA-Lewis Research Center (see fig. 14). This component was tested under both cruise and take off type conditions (ref. 10). As Figure 15 (ref. 11) shows, maximum liner temperature differences of about 200^{o} C were measured between the coated and uncoated conditions. In addition, in both cases, flame radiation was observed to decrease for the coated case indicating that the higher temperature oxide surfaces promoted more complete combustion and thus less carbon in the flame.

In burner rig combustion gas tests (ref. 12), even larger ΔTs have been observed. Such tests have shown (fig. 16) that these coatings have short time over-temperature capabilities to 1540^{o} C.

SOME ANALYTICAL RESULTS: THERMAL BARRIER COATINGS FOR UTILITY TURBINES

As shown in Figure 17, if thermal barrier coatings allow increases in turbine inlet temperatures (T.I.T.), distillate fired combined cycle engine efficiency will increase as expected and this results in lower costs of electricity (refs. 13 and 14). For residual fuel fired machines (fig. 18), analyses indicate airfoil life could be extended from 10 000 to 30 000 hours by lowering metal temperatures about 85^{o} C at a cost of 5 percent more cooling air, about 1 percent lower efficiency, and a slight increase in cost of electricity (refs. 14 and 15). However, a design life of 30 000 hours was also achievable with a thermal barrier coating. Here, calculated efficiency actually increased approximately 1 percent, cooling flow decreased 6 percent and cost of electricity dropped about 1 mill/kW-hr.

For calculations on recuperated cycle machines (based on ref. 16 efficiencies), the use of a thermal barrier also results in about 1 percent efficiency

increase over a wide range of pressure ratios. More importantly, perhaps, specific power also increased thus leading to more power per given capital cost.

Figure 19 shows some estimated fuel cost data (based on ref. 14) for a 300 MW combined cycle plant. Increases in efficiency achieved through higher turbine inlet temperatures made possible by the use of TBCs translate into substantial fuel cost savings per year, that is, \$1.7 M for an increase to 1200° C. However, if lower cost residual fuel could be fired instead of distillate - at no change in firing temperature - the savings calculated are around \$4.5 M/yr.

WHAT IS THE CURRENT STATUS OF THERMAL BARRIER COATINGS FOR INDUSTRIAL/UTILITY SERVICE?

Early data show that the zirconia coating compositions developed for clean fuel service have much shorter lives in the combustion gases of vanadium/sodium doped fuels. Several degradation mechanisms have been postulated but detailed analysis to isolate failure mechanisms has not yet been done. Plans are underway for an integrated program to answer such questions. The logic of such a program is summarized in Figure 20. In this approach the pay-off studies previously discussed serve to guide an effort to quantify the influence of potential fuel impurity attack on TBCs as well as to improve coating compositions so as to better resist such attack. Supporting this work are efforts to develop ways to uniformly and reproducibly deposit such coatings once compositions and microstructures are optimized. Finally, once coatings with promise for long time service in gas turbines burning a range of fuels have been developed, and can be uniformly, reproducibly, and economically applied to engine hardware, a decision can be made as to whether or not to proceed through component/coating design integration and finally to engine verification.

If such a decision is made, Figure 21 shows some of the ways the benefits of TBCs could be exploited. Here retrofit coating could be used to extend critical component life - either by lowering metal temperatures to extend creep life and/or by providing better overall resistance to fuel impurity hot corrosion. In partial redesign situations (dash engines) the more classic benefits of higher inlet temperatures with the same or lower cooling flows could be obtained. TBCs also offer a way to prolong the usefulness of lower cost, conventionally cast airfoil alloys or simple convection cooling in higher temperature cooled machines.

POINTS TO REMEMBER

In summary, there are a number of points to remember about thermal barrier coatings. First, they are in the early stages of development and at this time cannot be "painted on" to solve a design problem. Remember too, considerable time and effort were expended to develop and qualify the less complex aluminide and MCrAl overlay coatings. Still, the thermal barrier concept offers a more near term dirty fuel - higher temperature solution than ceramic airfoils. If TBCs are initially used to extend life, the coated airfoils will be much more failsafe than any ceramic blade or vane.

The benefits possible from such coatings have been discussed and early results offer hope that these benefits can be achieved. However, coating improvement, design technique development, design data, and engine test verification must yet be accomplished. Only then will thermal barrier coatings be ready for long term evaluation in industrial/utility gas turbines.

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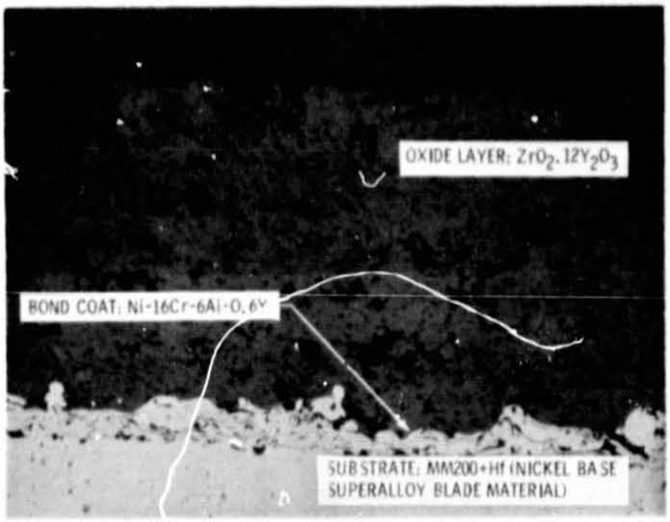

Figure 1. - Photomicrograph of the cross-section of a layered thermal barrier coating.

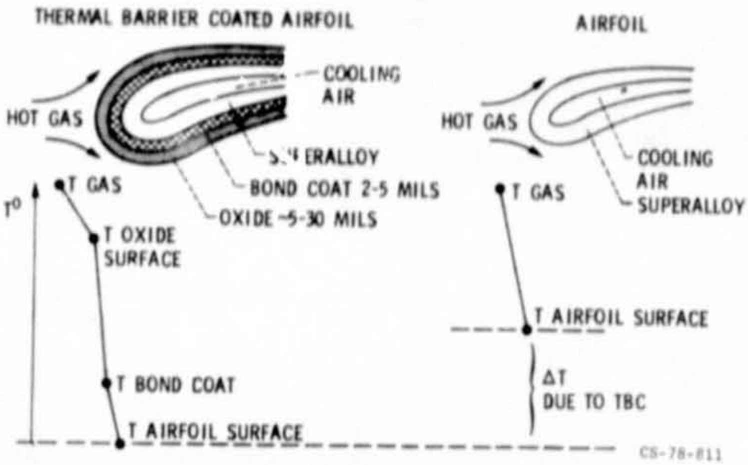

Figure 2. - Thermal barrier coatings (TBC): the concept.

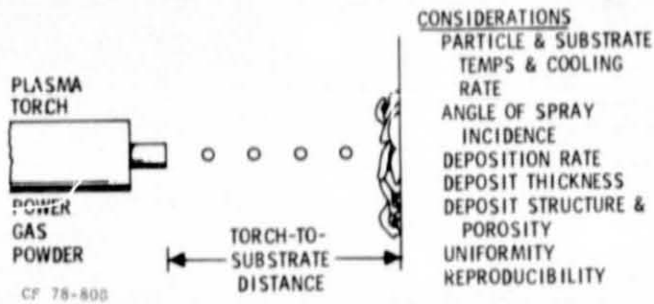

Figure 3. - Coating deposition.

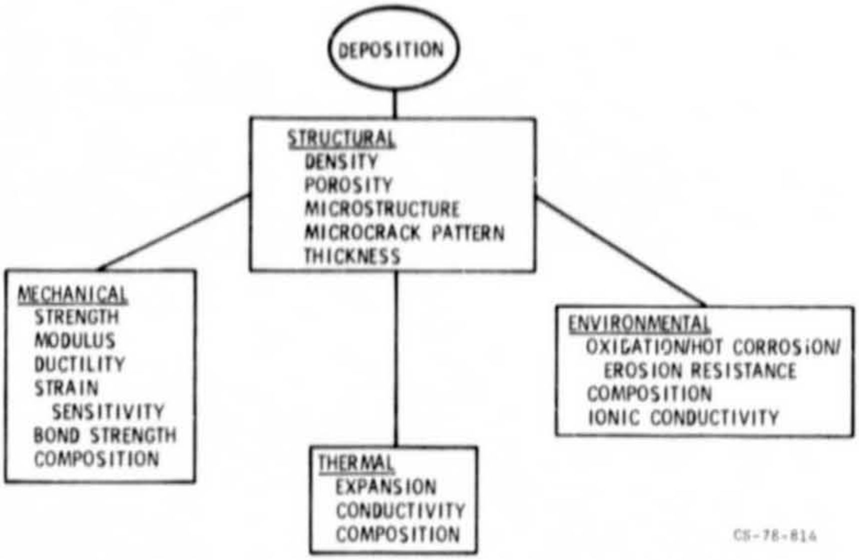

Figure 4. - As-sprayed properties to consider.

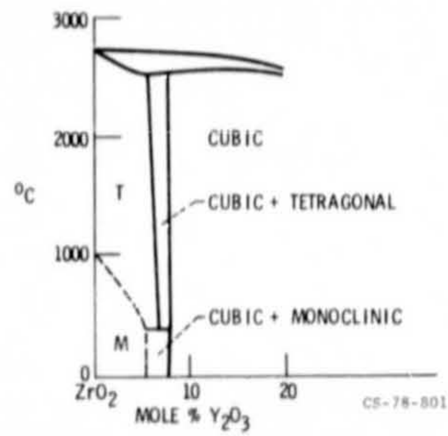

Figure 5. - Equilibrium binary phase diagram for zirconia-yttria system.

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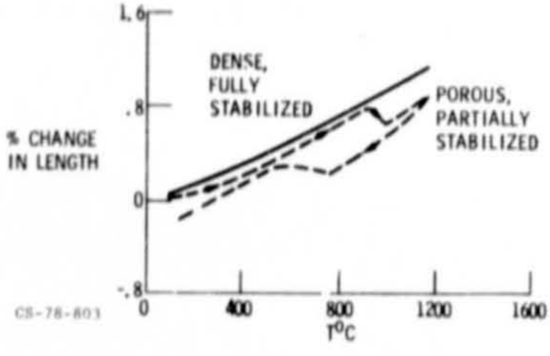

Figure 6. - Thermal expansion of zirconia.

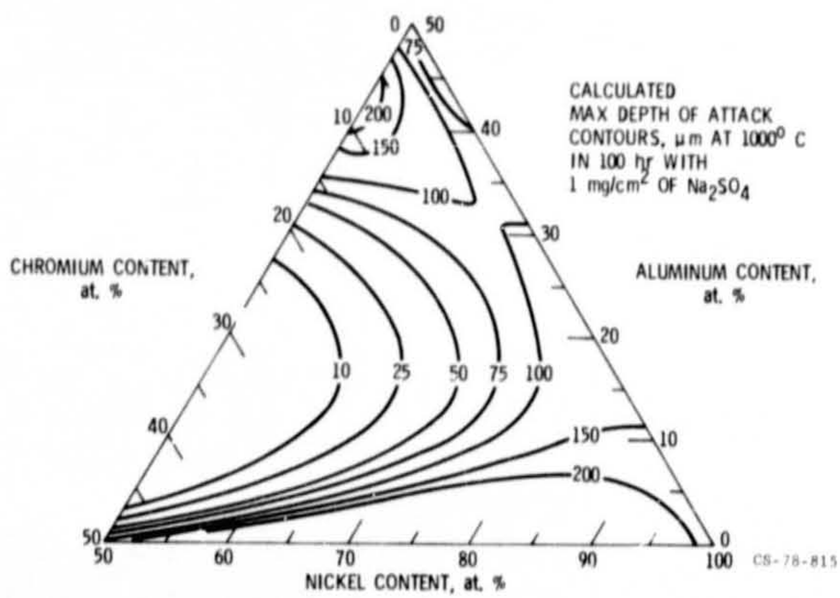

Figure 7. - Bond coating composition is also important.

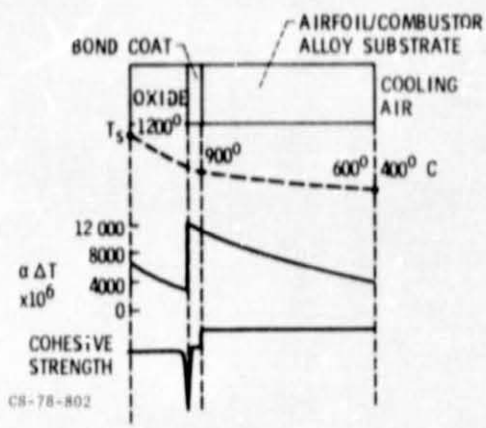

Figure 8. - Coating adherence considerations.

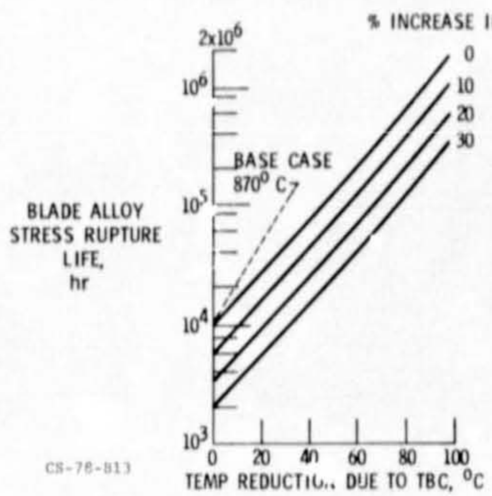

Figure 9. - Estimates of TBC effect on blade life.

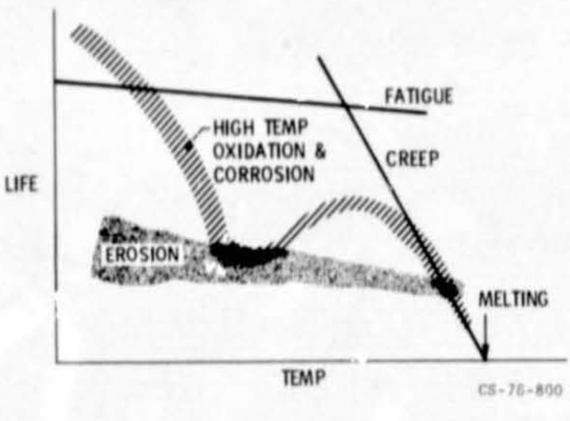

Figure 10. - Schematic of hot section component life controlling factors.

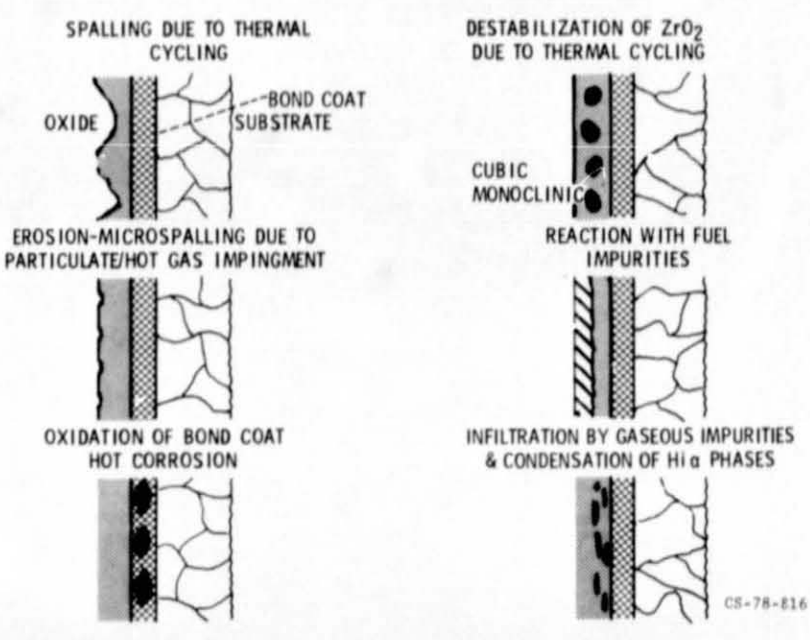

Figure 11. - Some potential failure mechanisms.

GAS TURBINE FOR:	GAS TEMP	FUEL QUALITY	DEVELOPMENT STAGE
AERONAUTICS	HIGH (T. I. T. TO ~1370° C)	GOOD (JET A/JP5)	EARLY (SOME RIG & ENGINE TEST)
GROUND POWER CLEAN FUEL	MOD (T. I. T. TO ~1090°-1100° C)	MOD (GT NO. 2)	VERY EARLY (SOME RIG DATA PUBL)
HEAVY FUEL	MOD-LOW	POOR (BLENDS & RESID)	EMBRYONIC

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Figure 12. - TBC's are at an early stage of development.

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Figure 13. - Ceramic coated turbine blades J 75 first stage rotor after 500 cycles operation 1370°C (2500°F) turbine inlet to flame out.

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Figure 14. - JT8D Combustor liner coated with NASA TBC.

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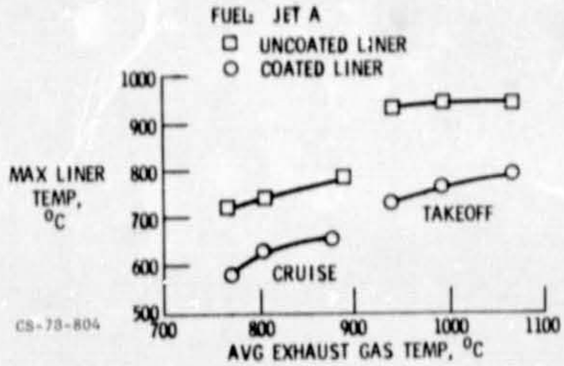

CS-78-804

Figure 15. - Effect of thermal barrier coating on maximum liner temperature.

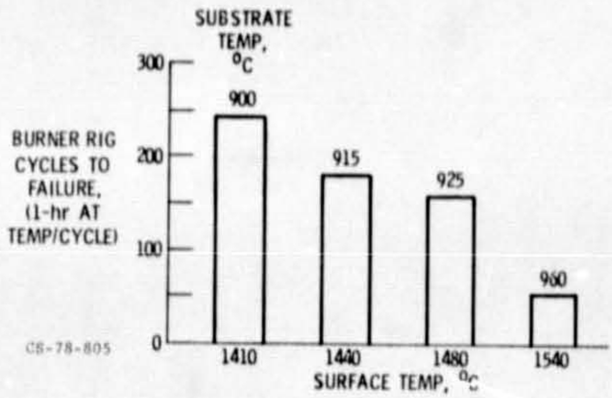

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Figure 16. - Thermal barrier coatings have over temperature potential.

	T. I. T., °C	EFFICIENCY, ηHHV	COE, MILLS/kW-hr
W-501 UNCOATED	1090-1150	41.49	33.741
W-501 + TBC	1204	42.68	32.747
W-501* + TBC	1315	43.86	31.791
ECAS-II** DESIGN + TBC	1370	***47	------

*ADVANCED CONVECTION COOLING SCHEME.
**16:1 PRESSURE RATIO.
***EITHER TRANSPIRATION COOLING OR TBC/CONVECTION.

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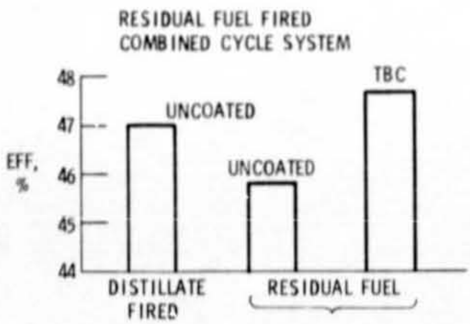
Figure 17. - Effect of using TBC to increase T. I. T.



TRIT, °C	1180	1180	1210
TMETAL, °C	900	815	815-900
AIRFOIL LIFE, 10^3 hr	10	30+	30 (PERIODIC REFURB OF TBC)
COOLING AIR FLOW, %	22	27	16
COE, MILLS/kW-hr	28.68	29.04	27.67

-78-812

Figure 18. - UTC FT50 performance comparison

	$/yr
INCREASED T. I. T.	
FROM 1090°-1145° C	
DISTILLATE FIRED*	
TO 1200°	1 700 000
TO 13[illegible]	3 300 000
FIRE RESIDUAL FUEL† AT $109[illegible]^{\circ}$ - 1145° C	4 500 000

*$2, 60/MBtu
†$2, 15/MBtu

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Figure 19. - Estimated cost savings for nominal 300 MW combined cycle plant (2 gas turbines).

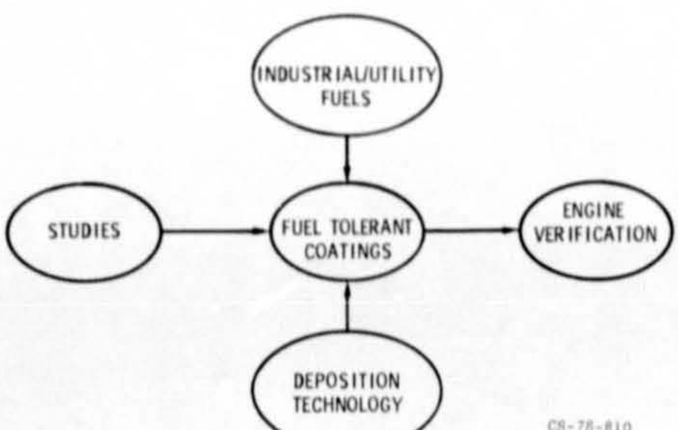

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Figure 20. - Program LOGIC.

RETROFIT MODE

- USE TBC TO LOWER METAL TEMPS & BUY MORE LIFE IN S-R/CREEP LIMITED DESIGNS
- USE TBC TO RESIST HOT CORROSION &/OR ACHIEVE SAME LIFE WITH LOWER COST FUEL

DASH ENGINE MODE

- USE TBC TO LOWER COOLING AIR FLOW & RAISE η
- USE TBC TO HOLD METAL TEMP/COOLING AIR FLOW CONSTANT AT HIGHER INLET TEMP
- USE TBC TO REGAIN OR MAINTAIN COOLING SIMPLICITY & EASILY CAST ALLOYS AT HIGHER INLET TEMPS & SAME COOLING FLOW

CS-78-809

Figure 21. - Potential ways to exploit TBC's in gas turbines.